SIMULATION OF LAGRANGIAN DRIFTERS IN THE LABRADOR SEA

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LONG-TERM GOALS

The long-term objective for this research is to use our improved knowledge of the TKE, Reynolds stress, and scalar flux budgets to develop and test parameterizations of mixed layer dynamics and deep penetrative convection and overturning for inclusion in basin-scale oceanic general circulation models.

OBJECTIVES

A principal technical objective is to simulate and understand the behavior of Lagrangian drifters and floats in the presence of deep convection in the Labrador Sea. The corollary scientific objective for the Labrador Sea Deep- Convection ARI is to understand the production, transport and dissipation of turbulent kinetic energy (TKE) and scalar variances (potential temperature and salinity); and the production and transport of covariances (Reynolds stresses, heat and salt fluxes) from drifter sensor systems.

APPROACH

A nonhydrostatic numerical model for high Reynolds number turbulent flow is used to predict convection. Large-Eddy Simulation (LES) has been adapted to prediction of nonhydrostatic ocean convection (Garwood et al., 1994; Paluszkiewicz et al., 1994) by including the important thermodynamic effects of the equation of state at low temperature and high pressure (Garwood, 1991) and consideration of appropriate ocean surface and bottom boundary conditions, and improvements in the spectral filter (Harcourt et al., 1998).

WORK COMPLETED

Large Eddy Simulation (LES) was used to study the physics of wintertime mixed layer deepening in the Labrador Sea. The LES simulations predict time series of mixed layer temperature, salinity and layer depth H that are verified by the hydrographic observations of the R/V Knorr in 1997. The effect of the turbulent fields on both fully Lagrangian and semi-Lagrangian 'Isobaric' drifters was simulated by modeling the motion of virtual drifters in tandem with the evolution of the LES fields. This research has resulted thus far in the publication of a Ph.D. dissertation (Harcourt, 1999), and several articles submitted.

RESULTS

The dependence of both the turbulent kinetic energy (TKE) and the rate of mixed layer deepening on the nonrotating free convective velocity scale $w^* = (B_0 H)^{1/3}$ and on the natural Rossby number $Ro^* =$

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w^*/fH were determined by varying the magnitude of planetary rotation f. The rate of entrainment work was parameterized in terms of the vertically integrated rate of work done against buoyancy forces on fluid entrained into the layer from the density interface, $w_e^{*3}/2$. The ratio of this TKE loss rate to the rate at which TKE is generated by hydrostatic adjustment to surface buoyancy loss, $-w_e^{*3}/w^{*3}$, generalizes the well known flux-ratio method to entrainment deepening where buoyancy is not a conserved property.

The Rossby number dependence for the convection, from Harcourt (1999) can be summarized as follows:

(i) All three components of TKE were found to have similar scaling in the absence of surface wind stress, with $q \sim w_{rms} \sim w^* Ro^{*p}$ for $0.05 < Ro^* < 1$, where $1/10 < p < 1/8$. This dynamic scaling is intermediate to nonrotating free convection, where $p = 0$, and full rotational control, where $p = 1/2$ implies that TKE is independent of H.

(ii) The scaling of vertical TKE was similar when wind stress was included, with $q \sim w_{rms} \sim w^* Ro^{*1/8}$.

(iii) When parameters other than rotation are held constant, it is found that $-w_e^{*3} \sim w^{*3} Ro^{*r}$, where the exponent of $r \approx 3p$ is consistent with the rotational scaling of w_{rms}^3/w^{*3}.

The subject of internal wave generation by deep convection has been raised by Garwood and Harcourt (1999a). This paper will be submitted to JGR. Of particular interest is the downward propagation of energy from the turbulent boundary layer by pressure transport and the build up of internal wave energy in response to local atmospheric forcing. A near equilibrium internal wave spectrum is approached after about two weeks of episodic storm cooling. A broad band omni-directional internal wave field with peak energy near the buoyancy frequency N is forced mostly by the buoyancy flux. The pressure transport of mixed-layer kinetic energy carries about 30% of the available energy into the stratified zone and causing entrainment. On average, $10^{-4} W/m^2$ or about 1% of the winter Labrador Sea mixed layer energy escapes into the pycnocline where it is converted into internal wave energy.

Results from Drifting Lagrangian Floats (DLF) deployed by D'Asaro during the winter 1997 cruise of the R/V Knorr have been compared with simulated model drifters incorporating drifter design features.

Model and real Lagrangian floats agree reasonably well with each other, and with the mean Eulerian LES profiles of vertical TKE, heat flux (Figures 1 - 2), and mean profiles of the Lagrangian budgets of vertical velocity and potential temperature. A kinematic model of the real Lagrangian drifters that were deployed by D'Asaro was used to examine the effects of certain non-Lagrangian float features. It was found that the drifters as designed would not be significantly affected by the intentional small differences between the compressibility of the drifters and the surrounding fluid. Additional unintended ballasting differences between the Lagrangian floats and the displaced fluid in 1997, on the order of several grams, were found to have small yet significant effects on simulated floats.

By comparing observed and simulated mean profiles of Eulerian statistics, Lagrangian budgets, and float distributions, it was possible to conclude with certainty that the 1997 DLF observations were not significantly affected by any unintended excess buoyancy, despite concerns to that effect. One feature of the 1997 DLF observations that was not replicated in the LES simulations is the presence of an additional vertical heat flux (Figure 2) in the upper quarter of the mixed layer, associated with augmented levels of vertical TKE (Figure 1). This feature was also evident in the profiles of the Lagrangian heat and vertical velocity budgets, and cannot be accounted for in a 1-dimensional model of the mixed layer that conserves heat. It indicates the presence of a dynamic process that exchanges heat laterally while mixing

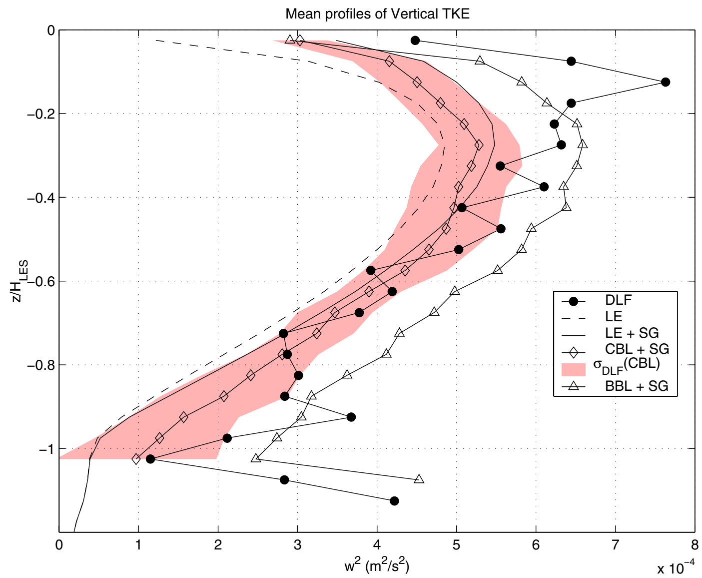

Figure 1: Mean profiles of vertical TKE component $\overline{w^2}$, plotted with respect to nondimensional depth, using the simulated mixed layer depth H_{LES}. Mean Eulerian profiles are shown for the numerically resolved (LE) and net (LE+SG) simulated vertical TKE. Mean simulated Lagrangian profiles shown for the CBL drifter model with the centrally ballasted (CBL + SG) design features, and for the buoyantly ballasted (BBL + SG) kinematic model with a mass deficit of 5 g, both include a contribution from subgrid energy along the drifter trajectories. Real profiles from drifting Lagrangian floats (DLF) can be compared with the net Eulerian and drifter model results that account for the subgrid (SG) contribution. Results from the correctly ballasted (CBL+SG) model floats are bracketted by a shaded region of $\pm\sigma_{DLF}(CBL)$ indicates the anticipated scatter in the experimental result using the standard deviation among mean CBL profiles from subensembles equivalent in size to the DLF sampling.

in the vertical, and contributes to the TKE production in the upper $100 - 200m$ of the mixed layer. This process is probably due to the interaction of Ekman circulation in a vertical plane in the presence of large of mesoscale horizontal gradients in temperature and buoyancy. Preliminary reports (E. Steffen, personal communication) on the 1998 DLF observations indicate that this feature was again observed, and in greater strength than in 1997.

Comparison of between the Isobaric drifters deployed in the Labrador Sea and those simulated in the LES model is in progress. Preliminary results from P/ALACE drifters deployed in the Labrador Sea in 1997 show a heat flux reduced to approximately half of the expected Eulerian value, as predicted by earlier LES results (Harcourt et al., 1998).

Related efforts to understand the effect of the non-Lagrangian behavior of these floats in the Greenland Sea and in previous Labrador Sea experiments has led to important results and deeper understanding of the behavior of floating material in a turbulent ocean (Garwood and Harcourt, 1998; Lherminier et al., 1999a). Mean vertical velocity measured by isobaric drifters during strong wintertime cooling events is a response to the small-scale turbulent convective structures responsible for homogenizing and deepening the mixed layer. Isobaric VCM floats deployed in the 1994 wintertime Greenland Sea measured significant vertical fluid transport during periods of strong surface heat loss. This phenomenon was successfully reproduced for an ensemble of model floats in a LES model of the deepening mixed layer in which larger mesoscale dynamics were not represented. Drifter data from previous experiments in the

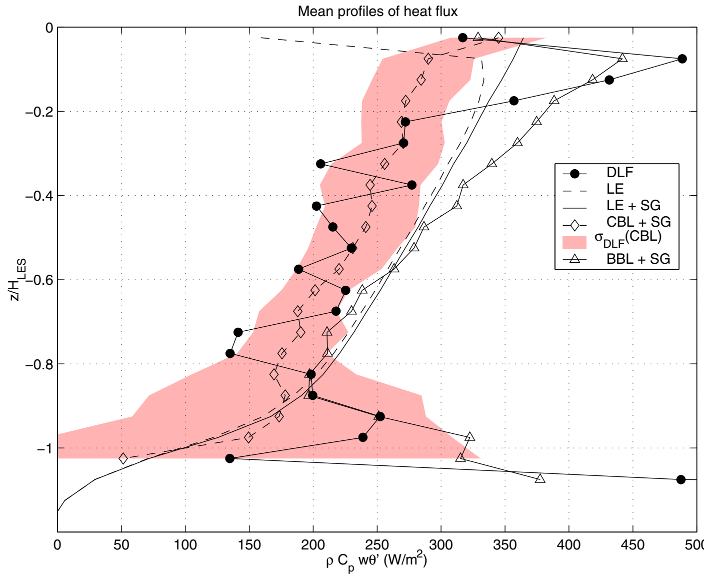

Figure 2: Mean profiles of vertical heat flux $\overline{w\theta'}$, plotted with respect to nondimensional depth, using the simulated mixed layer depth H_{LES}. Fluctuations θ' for the drifters were obtained from the time series of potential temperature using a highpass finite impulse response filter with a cutoff period of four days. Profiles shown here correspond to those in Figure 1, except that the subgrid contribution to the model Lagrangian profiles (CBL + SG, BBL + SG) was approximated by the Eulerian profile of unresolved flux.

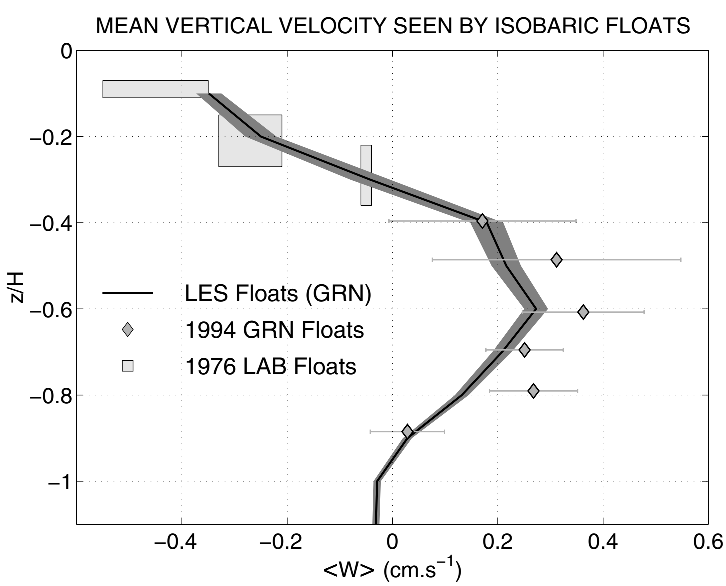

Figure 3: Profiles of mean vertical velocity. Model (LES) floats and experimental (94GRN) mean vertical velocity $\langle\overline{w}\rangle$ measured by isobaric floats from a simulation of deep convection in the Greenland Sea in 1994. The actual drifters are plotted as diamonds with horizontal error bars, and the solid line bracketed by a shaded region is the simulated ensemble mean and its uncertainty. Rescaled measurements from 1976 Labrador Sea (76LAB) appear as shaded rectangles.

Labrador Sea further confirm the modeling results (Figure 3).

IMPACT/APPLICATIONS

The results on Rossby number scaling have clear implications for large scale modeling. Deep convection in the Labrador Sea is significantly affected by planetary rotation, but not to such an extent that the dynamic length scale is set exclusively by surface buoyancy loss and the Coriolis parameter, as has been suggested in the literature. The effect of entrainment on mixed layer deepening remains significant, and a large scale model that neglects penetrative convection by relying on simple convective adjustment underestimates the convective production rate of Labrador Sea water.

The simulations of Lagrangian floats in the Labrador Sea, and comparisons between model and actual float statistics, have demonstrated that the Drifting Lagrangian Floats (DLF) deployed in the Labrador Sea are an accurate and effective tool for measuring deep convection. The model-experiment comparisons have revealed unanticipated features of the dynamics of deep convection which will be focussed on in future research efforts.

Preferential sampling of convergence zones by isobaric floats bears upon all measurements obtained with these instruments. In general, values obtained for the variance and covariance of vertical velocity and temperature fluctuations along drifter trajectories are significantly reduced by comparison to their Eulerian counterparts. This reduction is the direct result of the biased sampling by isobaric drifters which manifests in the appearance of net vertical fluid transport along drifter trajectories.

TRANSITIONS

The comparison of modeled and observed Lagrangian floats is in a final stage of analysis and writing, with a manuscript (Harcourt et al., 1999b) for early dissemination and for inclusion in a special Labrador Sea edition of JPO. An article on the interpretation of mean vertical velocity observed by isobaric floats has just been submitted to JMS (Lherminier et al., 1999b), and will be followed by an article focussing more broadly on the biases observed for Eulerian statistics obtained in simulations and experiments from drifters constrained to a fixed depth. Two remaining publications are anticipated for inclusion in the JPO volume. The first is a description of the LES model employed to simulate the motion of drifters, and the scaling relations found (Harcourt, 1999) for the dynamics of rotating convection in deep mixed layers. The second article will compare the results from P/ALACE floats in the Labrador Sea experiment with numerical results. A third article (Garwood and Harcourt, 1999b) will reconstruct the TKE and variance budgets for the wintertime Labrador Sea.

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